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February, 1956

ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

A Precision Potentiometer and Ratiometer
for use on Analogue Computers

by

R. J. Garvey, B.Sc. (Eng.)

FC

SUMMARY

This Memorandum gives design details of a precision potentiometer and ratiometer instrument suitable for use in setting up analogue computers. Voltages and voltage ratios of equal or opposite polarity can be measured with an accuracy of ± 1 part in 1000.

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1 General

In operating analogue computers such as Tridac it is necessary to measure voltages and voltage ratios to an accuracy of ± 1 part in 1000. A portable instrument has therefore been designed which can be used either as a potentiometer or as a ratiometer. The ratiometer measures the ratio of two voltages of equal or opposite polarity. The instrument described here was designed specifically for Tridac; it has the following performance:

Potentiometer range :	0 to 30 volts
Ratiometer range :	-100 to 1
Resolution :	1 part in 10,000
Accuracy :	± 1 part in 1000

The general arrangement of the instrument is shown by Fig.1. A selector switch is used to select the circuit required and the voltage or voltage ratio measured by adjusting four decade switches to balance the circuit.

Operating instructions for the instrument are appended.

2 Basic Circuits

2.1 Standardising Connection

Figure 2(a) shows the arrangement for standardising the potentiometer. The current i is adjusted so that the voltage across a standard resistance is equal and opposite to that of the standard cell. This produces a known voltage ($V = 30$ volts say) across the potentiometer.

2.2 Potentiometer

This circuit is shown by Fig.2(b). With the circuit balanced the unknown voltage is given as:

$$V_x = V \cdot \frac{P}{P + Q}$$

Unknown voltages of positive or negative polarity can be measured by reversing the battery connections as necessary. In practice the potentiometer resistance is a four dial unit as detailed by Fig.3. This arrangement permits the slider to be positioned with a resolution of 1 part in 10,000.

2.3 Positive Ratiometer

See Fig.2(c). This is a conventional circuit for measuring the ratio of two voltages of like polarity. It will be used, as is shown, for measuring the settings of coefficient potentiometers. These are used in the computer to set up coefficients or scale factors. If x is the fractional displacement of the slider on the coefficient potentiometer S , then when the circuit is balanced:

$$x = \frac{P}{P + Q}$$

The ratiometer resistance is in practice a four dial unit as for the previous circuit. The resistance r limits the current that would pass through an overload or short circuit at the output terminals; this protects the battery and four dial resistance unit.

The optimum values for the battery voltage and resistances in the circuit depend on the characteristics of the computer amplifiers; the values given on Fig.4 are designed for the standard computing amplifiers in Tridac. The design calculations are given in Appendix I.

4 Accuracy

The accuracy of measurement depends primarily on the accuracy of the precision resistors used. A practical tolerance on these is

$$\frac{\delta R}{R} = \pm 1 \text{ part in } 2000$$

The effect of this tolerance (see Appendix II) is to introduce errors in potential or ratio measurements of

$$\pm 1 \text{ part in } 1000.$$

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Appendices I to III
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APPENDIX I

Calculations

1 Battery Voltage and Resistance Values

The standard amplifier in Tridac has a working range of ± 30 volts and signal voltages do not normally exceed this value. A suitable battery voltage for the potentiometer circuit is therefore:

$$V_B = 31.5 \text{ volts}$$

The optimum values of the resistances in the ratiometer circuit of Fig.2(d) are governed by the amplifier characteristics. If the resistance of the variable arm is too small it will overload the amplifier, whereas it is not economical to wind precision resistors to give a resistance greater than 10,000 ohms. The standard amplifier supplies a maximum current of ± 4 milliamps into a load of 7,500 ohms and it is necessary to measure the gain of the amplifier without disconnecting this load. Referring to Fig.2(d) let:

i = total current supplied by amplifier

R_L = normal load resistor

R = maximum resistance of variable arm

$\frac{R}{k}$ = resistance of fixed ratio arm

k = multiplying factor

x = gain of computing circuit

V = voltage applied to ratiometer and computing circuit

when the circuit is balanced,

$$i = 7 \left(\frac{x}{R_L} + \frac{k}{R} \right);$$

this is a maximum when $x = k$, since k is always selected so that $0 < x < k$

$$\text{i.e.} \quad i_{\max} = 7k \left(\frac{1}{R_L} + \frac{1}{R} \right)$$

$$\text{let} \quad V = \frac{V'}{k}$$

where V' = the battery supply voltage

$$\text{then} \quad i_{\max} = V' \left(\frac{1}{R_L} + \frac{1}{R} \right)$$

let $i_{\max} < 4 \cdot 10^{-3}$ amps
 $V' = 15$ volts
 $R_L = 7500$ ohms
 then $R > 7500$ ohms
 say $R = 10,000$ ohms

In TRIDAG the gains of the computing circuits are within the range 0 to 100. Thus if R is calibrated to read 0 to 1 then suitable values for k are:

$$k = 1, 10 \text{ and } 100$$

The resistances required in the fixed ratio arm to give these values are:

$$\frac{R}{k} = 10,000, 1000 \text{ and } 100 \text{ ohms}$$

The supply voltages corresponding to these values of k are:

$$\frac{V'}{k} = 15, 1.5 \text{ and } 0.15 \text{ volts}$$

Voltages of approximately these magnitudes can be obtained by connecting via 1000 ohm resistors to the following tapping points on the battery:

$$V_B = 16.5, 3 \text{ and } 1.5 \text{ volts}$$

2 Galvanometer sensitivity

The galvanometer should be sufficiently sensitive to detect the smallest stud to stud displacement of the potentiometer or ratiometer switches but be sufficiently robust for use in a portable instrument. The greatest sensitivity is required for the two ratiometer circuits, as calculated below.

(a) Positive ratiometer

Referring to Fig.2(c) let

$V =$ battery voltage
 $R = P + Q$
 $\delta R =$ resistance per step of R
 $\delta i_g =$ galvanometer current when ratiometer is unbalanced by one step on R.

Solving the network to find i_g gives:

$$\delta i_g = V \cdot \frac{\delta R}{R} \cdot \frac{1}{G + (R + S)(1 - x)x}$$

which is a minimum when $x = \frac{1}{2}$, that is

$$(\delta i_g)_{\min} = V \cdot \frac{\delta R}{R} \cdot \frac{4}{4G + R + S}$$

let

V	$=$	15 volts
δR	$=$	1 ohm
R	$=$	10,000 ohms
S	$=$	7500 ohm
G	$=$	1000 ohm

then $(\delta i_g)_{\min} = 0.28$ microamps

(b) Negative ratiometer

Referring to Fig.2(d) let:

R	$=$	maximum resistance of variable arm
$\frac{R}{k}$	$=$	resistance of fixed arm
k	$=$	multiplying factor
δR	$=$	resistance per step of R
δi_g	$=$	galvanometer current when ratiometer is unbalanced by one step on R
$V = \frac{V'}{k}$	$=$	the applied voltage
V'	$=$	the battery voltage

solving the network to find δi_g gives:

$$\delta i_g = V' \cdot \frac{\delta R}{R} \cdot \frac{1}{G(1 + x) + \frac{R}{k} \cdot x}$$

This is a minimum when $x = k$, since $0 < x < k$.

Thus $(\delta i_g)_{\min} = V' \cdot \frac{\delta R}{R} \cdot \frac{1}{G(1 + k) + R}$

Let $V' = 15$ volts
 $\delta R = 1$ ohm
 $R = 10,000$ ohm
 $G = 1000$ ohm
 $k = 1$

then $\frac{(\delta i_g)_{\min}}{k} = 0.125$ microamps

A panel instrument which just detects these currents is as follows:

Size : 3 inch diameter

Resistance : 1000 ohm

Current for full scale deflection : 50-0-50 micro-amps.

APPENDIX II

Accuracy

1 Loading Errors

The circuit of Fig. 2(d) imposes a load on the amplifier and thus introduces an error due to the finite output impedance of the amplifier. The output impedance of the Tridac amplifier is

$$Z_o = \frac{x}{200}$$

where x = the gain of the computing circuit.

In this case it can be shown that the error in measuring the gain is

$$\frac{\delta x}{x} = \frac{1}{200 Q}$$

thus if

$$Q = 100 \text{ ohm}$$

$$\frac{\delta x}{x} = \frac{1}{20,000};$$

the error is thus negligibly small.

2 Resistance Errors

The effect of errors in the values of the precision resistors is calculated below for the three basic circuits of Figures 2(b), (c) and (d).

Figures 2(b) and (c)

Let δP = error in P
 δQ = error in Q
 δx = error in x

then $x = \frac{P}{P + Q}$

$$(x + \delta x) = \frac{P + \delta P}{(P + \delta P) + (Q + \delta Q)}$$

whence $\frac{\delta x}{x} = (1 - x) \left(\frac{\delta P}{P} - \frac{\delta Q}{Q} \right)$

$\frac{\delta P}{P}$ and $\frac{\delta Q}{Q}$ are manufacturing tolerances which are independent of the values of P , Q and therefore x . Hence

$$\left(\frac{\delta x}{x} \right)_{\max} = \frac{\delta P}{P} + \frac{\delta Q}{Q}.$$

If $\frac{\delta P}{P} = \pm \frac{1}{2000}$

and $\frac{\delta Q}{Q} = \pm \frac{1}{2000}$

then $\frac{\left(\frac{\delta x}{x}\right)_{\max}}{\quad} = \pm \frac{1}{1000}$

Figure 2(a)

Let δP = error in P
 δQ = error in Q
 δx = error in x

then $x = \frac{P}{Q}$

$$(x + \delta x) = \frac{P + \delta P}{Q + \delta Q}$$

whence $\frac{\delta x}{x} = \frac{\delta P}{P} - \frac{\delta Q}{Q}$

If $\frac{\delta P}{P} = \pm \frac{1}{2000}$

and $\frac{\delta Q}{Q} = \pm \frac{1}{2000}$

then $\frac{\delta x}{x} = \pm \frac{1}{1000}$

APPENDIX III

Operating Instructions

1 General

The galvanometer sensitivity switch should be turned to the minimum position except when making final balancing adjustments.

The instrument operates from an internal battery and there is a small but steady drain on this when the instrument is switched on. The circuit selector should therefore be turned to the OFF position except when measurements are actually being made.

2 To Measure Potential

The instrument must first be standardised as shown by Fig.2(a). Select STANDARDISE on the circuit selector and adjust the current until the galvanometer reads zero. The galvanometer takes current from the standard cell during this operation; the galvanometer key should therefore only be depressed momentarily to obtain a reading; this will keep the drain on the standard cell to a minimum. Check the standardisation immediately before and after each potential measurement.

Connect external circuit as in Fig.2(b) and note polarity and approximate magnitude of unknown voltage on the voltmeter. Select POTENTIAL X30 or POTENTIAL X-30 on circuit selector according to polarity of unknown voltage. Now adjust the decade dials until the galvanometer reads zero. The unknown voltage is given as the product of the dial readings and ± 30 volts.

3 Setting Coefficient Potentiometers

Connect the coefficient potentiometer as in Fig.2(c) and select RATIO X1 on the circuit selector. To set up a particular coefficient adjust the decade dials to the required value and then position the slider on the coefficient potentiometer until the galvanometer reads zero. Alternatively to check a given setting, balance the circuit with the decade dials. The dial readings in either case correspond to the fractional displacement of the slider on the coefficient potentiometer or to the voltage ratio $V_x : V$. An approximate measurement of the ratio can be made by switching the voltmeter to read V_x and V directly.

The voltage V should be steady at 15 volts (with the coefficient potentiometer disconnected). If it is not so replace the battery.

The coefficient potentiometer will normally have a resistance of 7500 ohms. Measurements can be made with potentiometers of smaller resistances but these will tend to overload the internal battery.

4 To Set or Measure Amplifier Gain

Connect the instrument as in Fig.2(d) the COMMON terminal being connected to signal earth. Select RATIO X-1, X-10 or -100 according to the nominal gain of the amplifier circuit. Check that the amplifier has not drifted by shorting the input and measuring the output voltage V_x ; this should be within ± 5 millivolts. Measure input and output voltage of amplifier circuit on the voltmeter. The output voltage should be less than 15 volts, otherwise the amplifier may be overloaded. If the output is not less than 15 volts select a more suitable range with the circuit selector but do not select a lower range than is necessary.

To set up a particular gain adjust the decade dials to the required value and then adjust the gain of the amplifier circuit until the galvanometer reads zero. Alternatively, to check a given gain, balance the circuit with the decade dials. The gain is given as the product of the dial readings and the multiplying factor selected on the circuit selector.

The voltage V should be steady at about 15, 1.5 or 0.15 volts according to the range selected. If it is not steady at these values replace the battery.

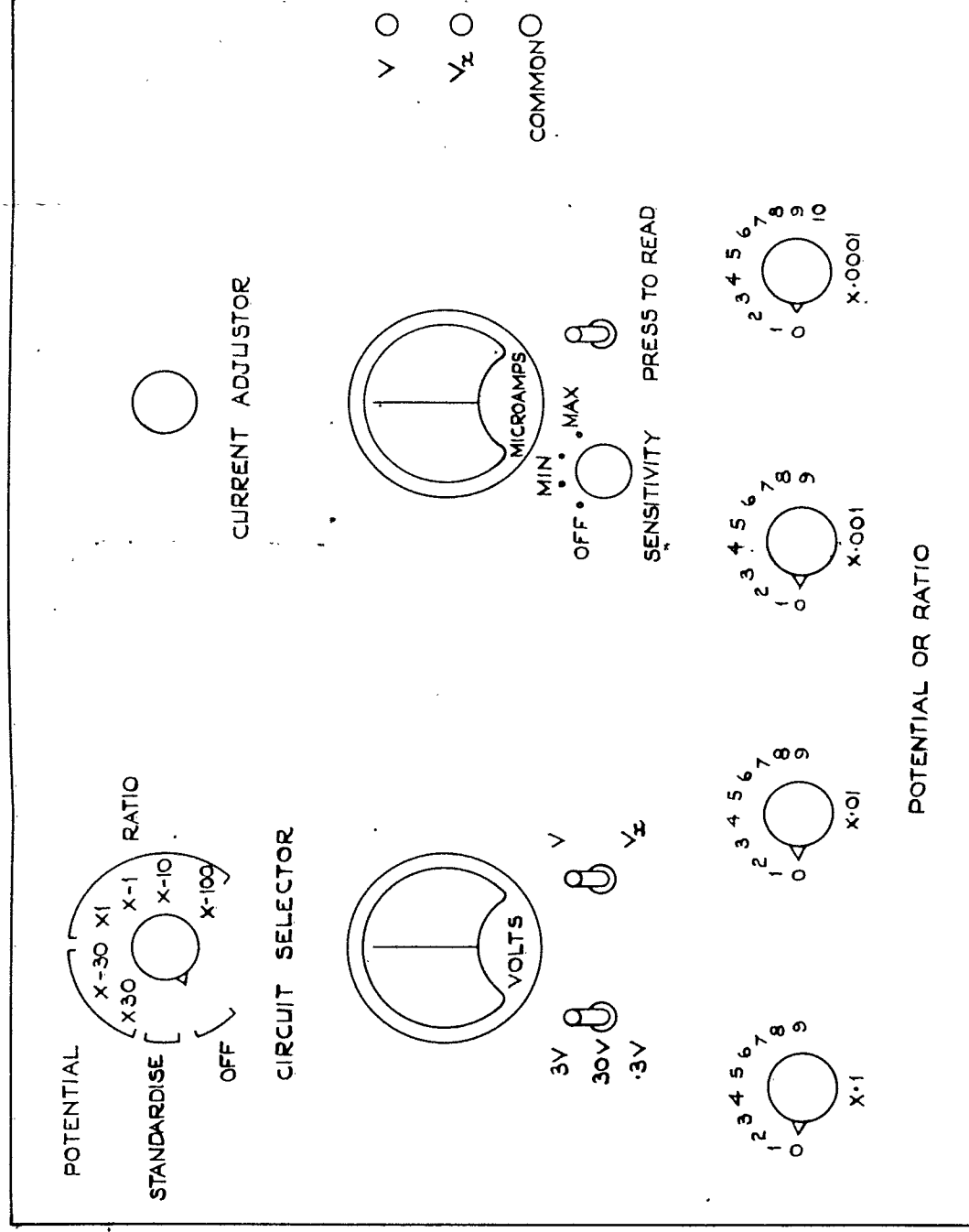
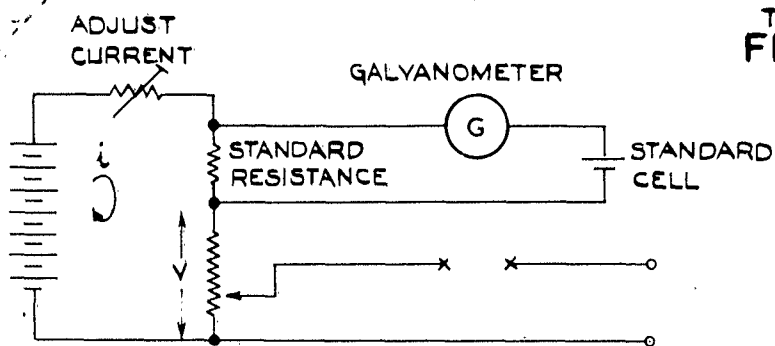
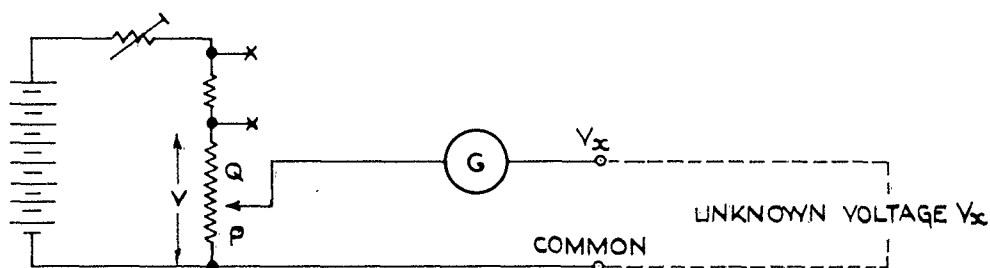


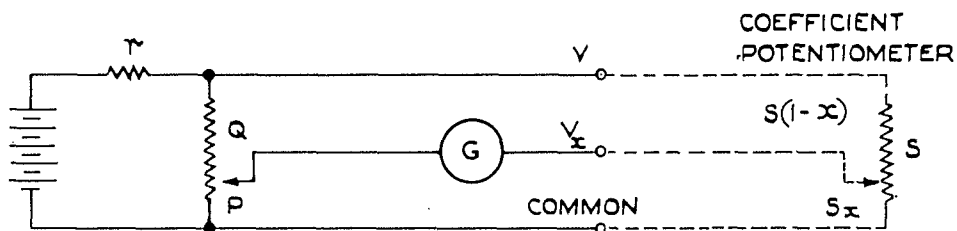
FIG. I. PANEL LAYOUT.



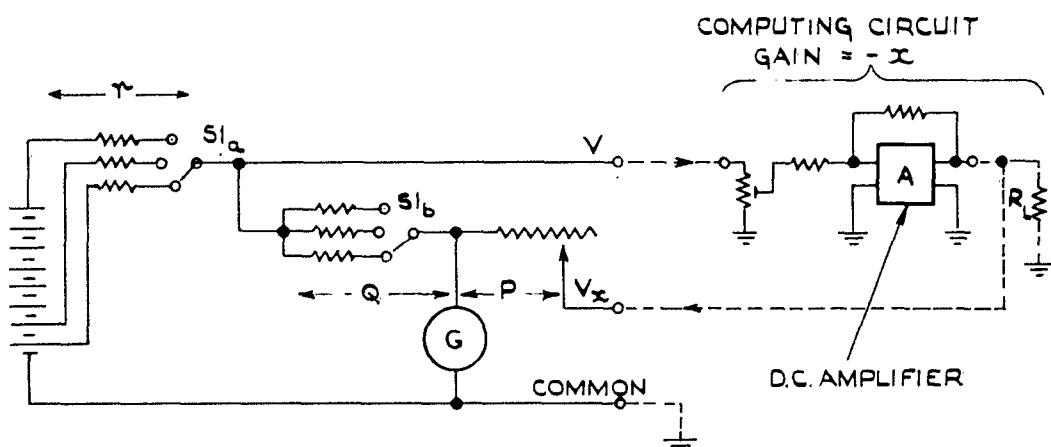
(a) STANDARDISING CONNECTION



(b) POTENTIOMETER



(c) POSITIVE RATIOMETER



(d) NEGATIVE RATIOMETER

FIG.2. (a,b,c & d) BASIC CIRCUITS.

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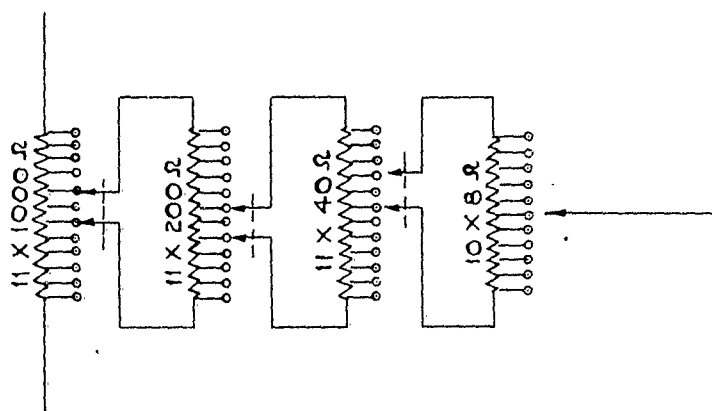
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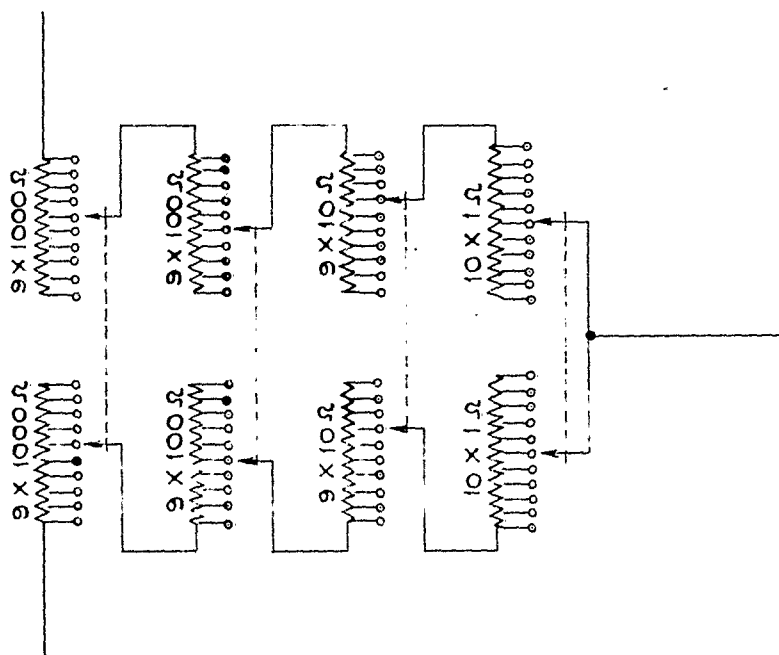
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FIG. 3.(a & b)



(a) KELVIN -VARLEY SLIDE.

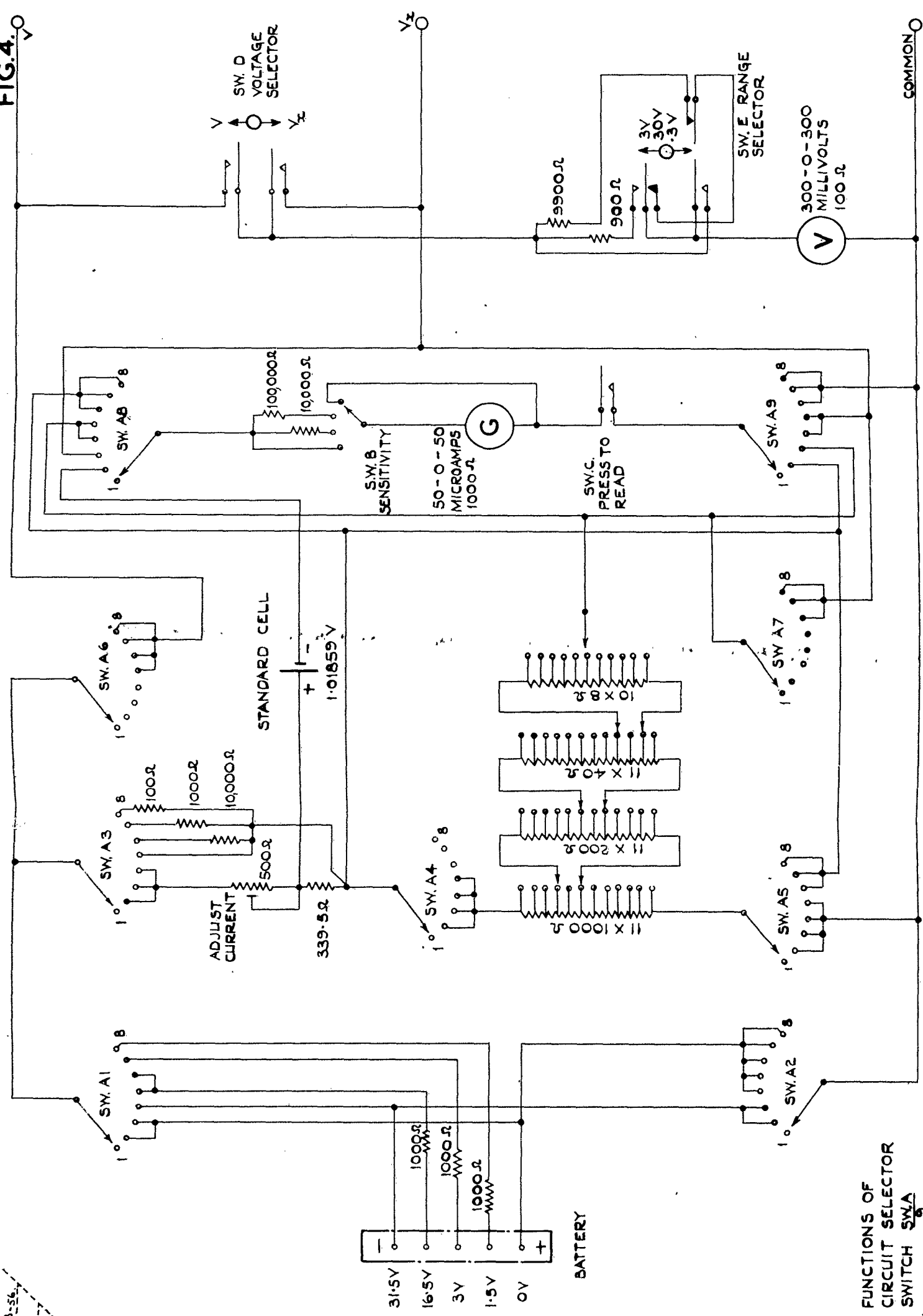


(b) ALTERNATIVE ARRANGEMENT.

FIG. 3.(a & b) VOLTAGE DIVIDING CIRCUITS.

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 FIG. 4.



FUNCTIONS OF
 CIRCUIT SELECTOR
 SWITCH SW. A

POSITION	FUNCTION
1	OFF
2	STANDARDISE
3	POTENTIOMETER POSITIVE INPUT
4	POTENTIOMETER NEGATIVE INPUT
5	RATIOMETER $k = 1$
6	RATIOMETER $k = -1$
7	RATIOMETER $k = -10$
8	RATIOMETER $k = -100$

FIG. 4. WIRING DIAGRAM.



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